

The Science Case for STEP

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Abstract

STEP (the Satellite Test of the Equivalence Principle) will advance experimental limits on violations of Einstein's equivalence principle (EP) from their present sensitivity of 2 parts in 10^{13} to 1 part in 10^{18} through multiple comparison of the motions of four pairs of test masses of different compositions in an earth-orbiting drag-free satellite. Dimensional arguments suggest that violations, if they exist, should be found in this range, and they are also suggested by leading attempts at unified theories of fundamental interactions (e.g. string theory) and cosmological theories involving dynamical dark energy. Discovery of a violation would constitute the discovery of a new force of nature and provide a critical signpost toward unification. A null result would be just as profound, because it would close off any possibility of a natural-strength coupling between standard-model fields and the new light degrees of freedom that such theories generically predict (e.g., dilatons, moduli, quintessence). STEP should thus be seen as the intermediate-scale component of an integrated strategy for fundamental physics experiments that already includes particle accelerators (at the smallest scales) and supernova probes (at the largest). The former may find indirect evidence for new fields via their missing-energy signatures, and the latter may produce direct evidence through changes in cosmological equation of state—but only a gravitational experiment like STEP can go further and reveal how or whether such a field couples to the rest of the standard model. It is at once complementary to the other two kinds of tests, and a uniquely powerful probe of fundamental physics in its own right.

1 Historical Overview

The Satellite Test of the Equivalence Principle (STEP; Fig. 1) will probe the

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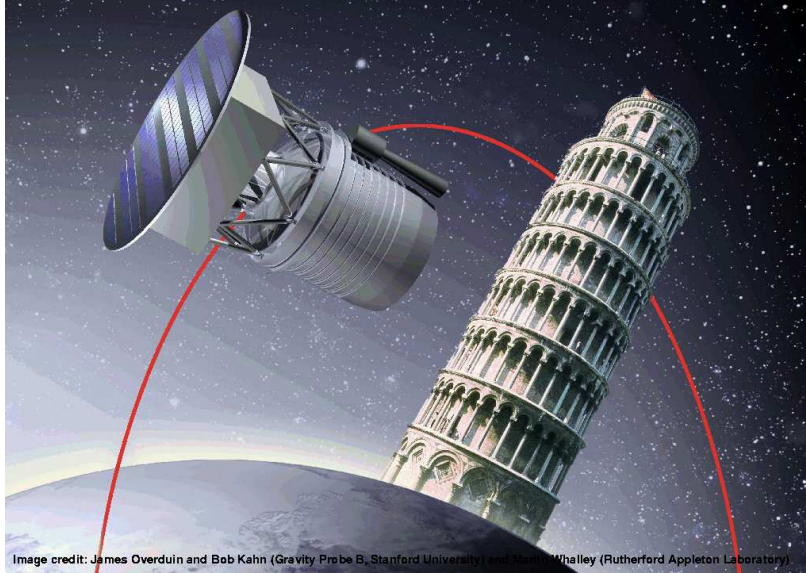


Fig. 1. Artists' impression of the STEP spacecraft

foundation of Einstein's theory of general relativity, the (local) equivalence of gravitational and inertial mass—more specifically called the weak equivalence principle—to unprecedented precision. The equivalence principle (EP) originated in Newton's clear recognition (1687) of the strange experimental fact that mass fulfills two conceptually independent functions in physics, as both the source of gravitation and the seat of inertia. Einstein's “happiest thought” (1907) was the recognition that the equivalence of gravitational and inertial mass allows one to locally “transform away” gravity by moving to the same accelerated frame, regardless of the mass or composition of the falling object. It followed that the phenomenon of gravitation could not depend on any property of matter, but must rather spring from some property of spacetime itself. Einstein identified the property of spacetime that is responsible for gravitation as its curvature. General relativity, our currently accepted “geometrical” theory of gravity, thus rests on the validity of the EP. But it is now widely expected that general relativity must break down at some level in order to be united with the other fields making up the standard model of particle physics. It therefore becomes imperative to test the EP as carefully as possible.

Historically, equivalence has been tested in four distinct ways: (1) Galileo's free-fall method, (2) Newton's pendulum experiments, (3) Newton's celestial method (his dazzling insight that moons and planets could be used as test masses in the field of the sun) and (4) Eötvös' torsion balance. Certain kinds of EP violation can also be constrained by other phenomena such as the polarization of the cosmic microwave background (Ni, 2008). However, the most robust and sensitive EP tests to date have come from approaches (3) and (4). The celestial method now makes use of lunar laser ranging to place limits on the relative difference in acceleration toward the sun of the earth and moon of $(-1.0 \pm 1.4) \times 10^{-13}$ (Williams et al., 2004), and modern state-of-the-art

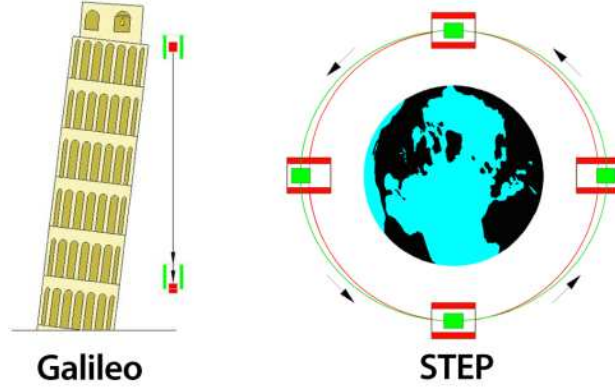


Fig. 2. Compared with Galileo at Pisa, STEP employs a “tower” not 60 m but 7000 km high, and one constantly reversing its direction to give a continuous periodic signal rather than a quadratic 3 s drop.

torsion balance experiments give comparable constraints of $(0.3 \pm 1.8) \times 10^{-13}$ (Schlamminger et al., 2008). Both these methods have reached an advanced level of maturity and it is unlikely that they will advance significantly beyond the 10^{-13} level in the near term.

STEP is conceptually a return to Galileo’s free-fall method, but one that uses a 7000 km high “tower” that constantly reverses its direction to give a continuous periodic signal, rather than a quadratic 3 s drop (Fig. 2). A free-fall experiment in space has two principal advantages over terrestrial torsion-balance tests: a larger driving acceleration (sourced by the entire mass of the earth) and a quieter “seismic” environment, particularly if drag-free technology is used. These factors alone lead to an increase in sensitivity over current methods of three orders of magnitude each. Comprehensive numerical disturbance analysis (Worden et al., 2001) has established that 20 orbits (1.33 days) of integration time will suffice for STEP to improve on existing EP constraints by *five to six orders of magnitude*, from $\sim 10^{-13}$ to 10^{-18} .

There are other proposed experiments to test the EP in space; most notable is MicroSCOPE, a room-temperature mission that will fly two accelerometers with a measurement goal of 10^{-15} . MicroSCOPE was conceived by the ONERA group (part of the STEP collaboration) and is funded by CNES and ESA with a possible launch date of 2011. This paper will focus on STEP, which while not yet approved for flight, has been through Phase A studies sponsored by NASA and ESA, and promises a large improvement in sensitivity.

2 Experimental Design

The STEP design calls for four pairs of concentric test masses, currently composed of Pt-Ir alloy, Nb and Be in a cyclic condition to eliminate possible

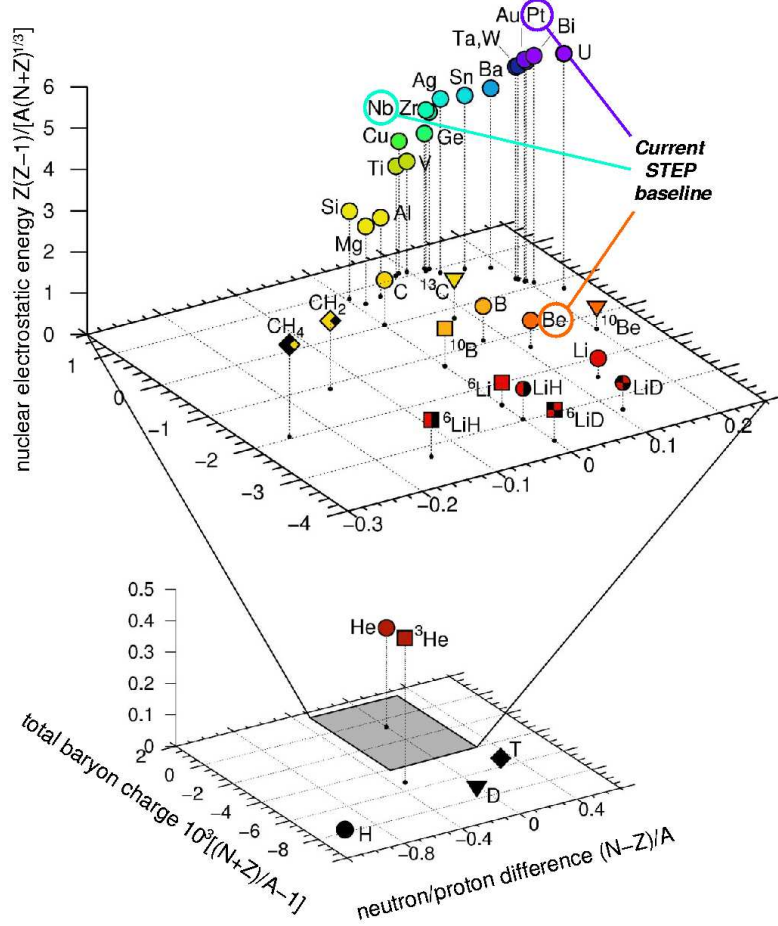


Fig. 3. Test mass choice. A theoretical approach might be to span the largest possible volume in the space of string-inspired “elementary charges” such as baryon number $N + Z$, neutron excess $N - Z$ and nuclear electrostatic energy $[\propto Z(Z - 1)]$, all normalized by atomic mass A (see text). This approach must be balanced against practical issues such as manufacturability, cost, and above all the need to make sure that anything measured is a real effect.

sources of systematic error (the total acceleration difference between A-B, B-C and C-A must be zero for three mass pairs AB, BC and CA). This choice of test-mass materials is not yet fixed, but results from extensive theoretical discussions suggesting that EP violations are likely to be tied to three potential determinative factors that can be connected to a general class of string-inspired models: baryon number, neutron excess and nuclear electrostatic energy [Fig. 3; Damour and Blaser (1994); Damour (1996); Blaser (2001)]. The test masses are constrained by superconducting magnetic bearings to move in one direction only; they can be perfectly centered by means of gravity gradient signals, thus avoiding the pitfall of most other free-fall methods (unequal initial velocities and times of release). Their accelerations are monitored with very soft magnetic “springs” coupled to a cryogenic SQUID-based readout system. The SQUIDS are inherited from Gravity Probe B, as are many of the other key STEP technologies, including test-mass caging mechanisms, charge

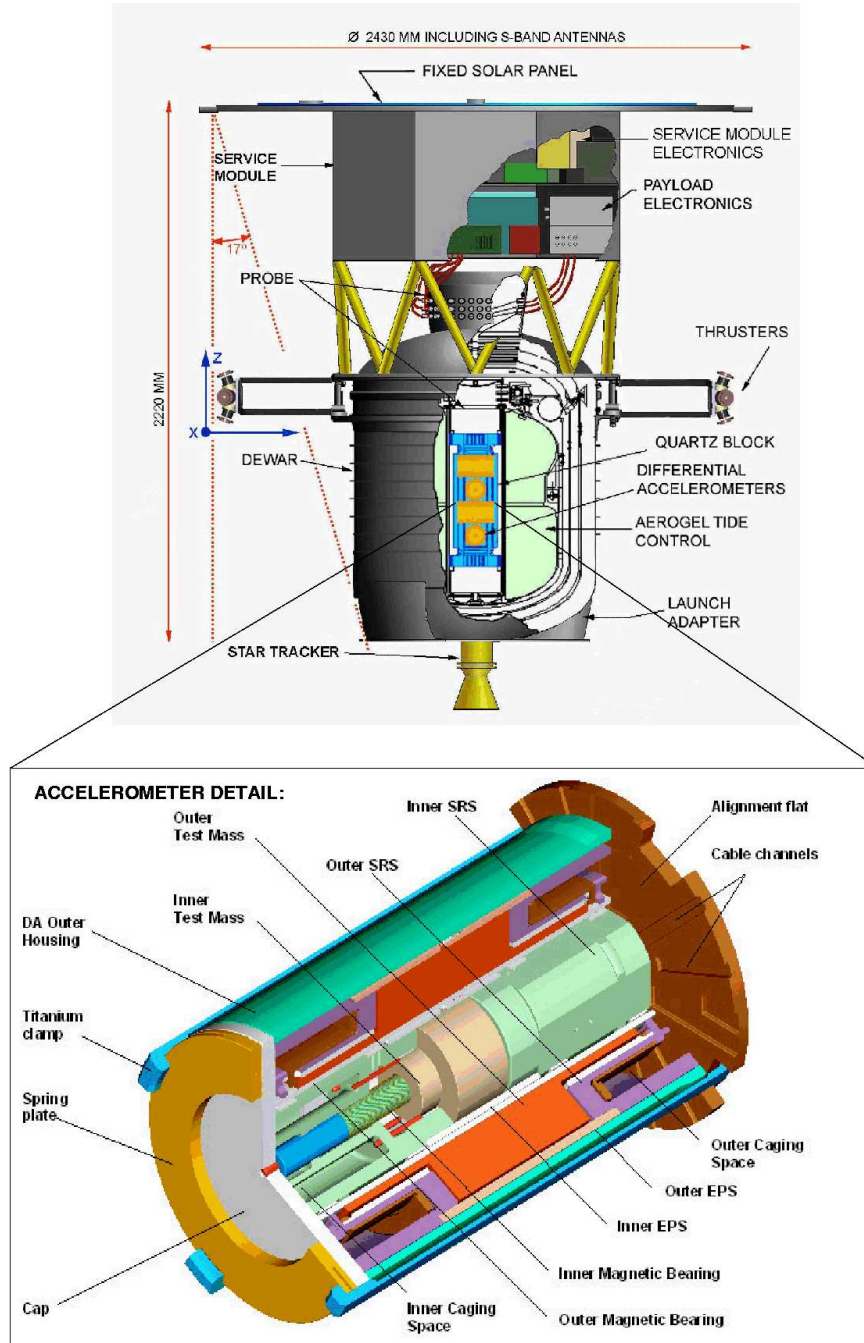


Fig. 4. Cutaway view of the STEP spacecraft (top) with accelerometer detail (bottom; DA=Differential Accelerometer, EPS=Electrostatic Positioning System, SRS=Squid Readout Sensor). Each accelerometer contains two concentric test masses, cylindrical in shape but with dimensions chosen to make them gravitationally “spherical” to sixth order in mass moments.

measurement and UV discharge systems, drag-free control algorithms and proportional helium thrusters using boiloff from the dewar as propellant (Fig. 4). Prototypes of key components including the accelerometer are in advanced stages of development.

3 Theoretical Motivation

Theoretically, the range $10^{-18} \lesssim \Delta a/a \lesssim 10^{-13}$ is an extremely interesting one. This can be seen in at least three ways. The simplest argument is a dimensional one. New effects in any theory of quantum gravity must be describable at low energies by an effective field theory with new terms like $\beta(m/m_{\text{QG}}) + O(m/m_{\text{QG}})^2$ where β is a dimensionless coupling parameter not too far from unity and m_{QG} is the quantum-gravity energy scale, which could be anywhere between the grand unified theory (GUT) scale $m_{\text{GUT}} \sim 10^{16}$ GeV and the Planck scale $m_{\text{Pl}} \sim 10^{19}$ GeV. In a theory combining gravity with the standard model of particle physics, m could plausibly lie anywhere between the mass of an ordinary nucleon ($m_{\text{nuc}} \sim 1$ GeV) and that of the Higgs boson ($m_{\text{H}} \sim 100$ GeV). With these numbers one finds that EP-violating effects should appear between $(m_{\text{nuc}}/m_{\text{Pl}}) \sim 10^{-19}$ and $(m_{\text{H}}/m_{\text{GUT}}) \sim 10^{-14}$ —exactly the range of interest. Adler (2006) has noted that this makes STEP a potential probe of quantum gravity.

The dimensional argument, of course, is not decisive. A second approach is then to look at the broad range of specific theories that are sufficiently mature to make quantitative predictions for EP violation. There are two main categories. On the high-energy physics side, EP violations occur in many of the leading unified theories of fundamental interactions, notably *string theories* based on extra spatial dimensions. In the low-energy limit, these give back classical general relativity with a key difference: they generically predict the existence of a four-dimensional scalar dilaton partner to Einstein’s tensor graviton, and several other gravitational-strength scalar fields known as moduli. In the early universe, these fields are naturally of the same order as the gravitational field, and some method has to be found to get rid of them in the universe we observe. If they survive, they will couple to standard-model fields with the same strength as gravity, producing drastic violations of the EP. One conjecture is that they acquire large masses and thus correspond to very short-range interactions, but this solution, though widely accepted, entails grave difficulties (the Polonyi or “moduli problem”) because the scalars are so copiously produced in the early universe that their masses should long ago have overclosed the universe, causing it to collapse. Another possibility involves a mechanism whereby a massless “runaway dilaton” (or moduli) field is cosmologically attracted toward values where it almost, but not quite, decouples from matter; this results in EP violations that overlap the range identified above and might in principle reach the $\sim 10^{-12}$ level (Damour et al., 2002). Similar comments apply to another influential model, the TeV “little string” theory (Antoniadis et al., 2001).

The second category of specific EP-violating theories occurs at the opposite extremes of mass and length, in the field of cosmology. The reason, however,

is the same: a new field is introduced whose properties are such that it should naturally couple with gravitational strength to standard-model fields, thus influencing their motion in violation of the EP. The culprit in this case is typically *dark energy*, a catch-all name for the surprising but observationally unavoidable fact that the expansion of the universe appears to be undergoing late-time acceleration. Three main explanations have been advanced for this phenomenon: either there is a cosmological constant (whose value is extremely difficult to understand), or general relativity is incorrect on the largest scales—or dark energy is *dynamical*. Most theories of dynamical dark energy (also known as quintessence) involve one or more species of new, light scalar fields that could violate the EP (Bean et al., 2005). The same thing is true of new fields that may be responsible for producing cosmological variations in the values of fundamental constants such as the electromagnetic fine-structure constant α (Dvali and Zaldarriaga, 2002).

In all or most of these specific theories, EP violations typically appear within the STEP range, $10^{-18} \lesssim \Delta a/a \lesssim 10^{-13}$. To understand the reasons for this, it is helpful to look at the third of the arguments alluded to above for regarding this range as a particularly rich and interesting one from a theoretical point of view. This line of reasoning shares some of the robustness of the dimensional argument, in that it makes the fewest possible assumptions beyond the standard model, while at the same time being based upon a convincing body of detailed calculations. Many authors have done work along these lines, with perhaps the best known being that of Carroll (1998) and Chen (2005), which we follow in outline here. Consider the simplest possible new field: a scalar ϕ (as motivated by observations of dark energy, or alternatively by the dilaton or supersymmetric moduli fields of high-energy unified theories such as string theory). Absent some protective symmetry (whose existence would itself require explanation), this new field ϕ couples to standard-model fields via dimensionless coupling constants β_k (one for each standard-model field) with values not too far from unity. Detailed calculations within the standard model (modified only to incorporate ϕ) show that these couplings are tightly constrained by existing limits on violations of the EP. The current bound of order $\Delta a/a < 10^{-12}$ translates directly into a requirement that the dominant coupling factor (the one associated with the gauge field of quantum chromodynamics or QCD) cannot be larger than $\beta_{\text{QCD}} < 10^{-6}$. This is very small for a dimensionless coupling constant, though one can plausibly “manufacture” dimensionless quantities of this size (e.g. $\alpha^2/16\pi$), and many theorists would judge that anything smaller is almost certainly zero. Now STEP will be sensitive to violations as small as 10^{-18} . If none are detected at *this* level, then the corresponding upper bounds on β_{QCD} go down like the square root of $\Delta a/a$; i.e., to $\beta_{\text{QCD}} < 10^{-9}$, which is no longer a natural coupling constant by any current stretch of the imagination. For perspective, recall the analogous “strong CP” problem in QCD, where a dimensionless quantity of order 10^{-8} is deemed so unnatural that a new particle, the axion, must be invoked to

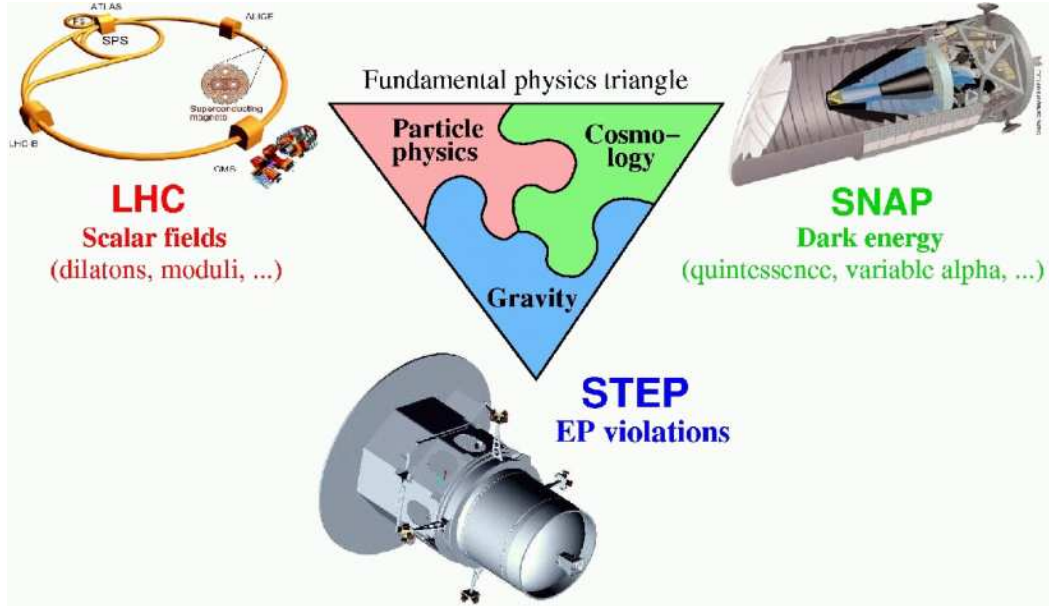


Fig. 5. Investigating nature on all three scales: small, large—and *intermediate*

drive it toward zero. This argument does not say that EP violations inside the STEP range are inevitable; rather it suggests that violations *outside* that range would be so unnaturally fine-tuned as to not be worth looking for. As Ed Witten has stated, “It would be surprising if ϕ exists and would not be detected in an experiment that improves bounds on EP violations by 6 orders of magnitude” (Witten, 2000). *Only a space test of the EP has the power to force us to this conclusion.*

The fundamental nature of the EP makes such a test a win-win proposition, regardless of whether violations are actually detected. A positive detection would be equivalent to the discovery of a new force of nature, and our first signpost toward unification. A null result would imply either that no such field exists, or that there is some deep new symmetry that prevents its being coupled to SM fields. A historical parallel to a null result might be the Michelson-Morley experiment, which reshaped physics because it found nothing. The “nothing” finally forced physicists to accept the fundamentally different nature of light, at the cost of a radical revision of their concepts of space and time. A non-detection of EP violations at the 10^{-18} level would strongly suggest that gravity is so fundamentally different from the other forces that a similarly radical rethinking will be necessary to accommodate it within the same theoretical framework as the SM based on quantum field theory.

STEP should be seen as the integral intermediate-scale element of a concerted strategy for fundamental physics experiments that already includes high-energy particle accelerators (at the smallest scales) and cosmological probes (at the largest scales), as suggested in Fig. 5. Accelerators such as the Large Hadron Collider (LHC) may provide indirect evidence for the existence

of new fields via their missing-energy signatures. Astronomical observatories such as the SuperNova Acceleration Probe (SNAP) may produce *direct* evidence of a quintessence-type cosmological field through its bulk equation of state. But *only a gravitational experiment such as STEP can go further and reveal how or whether that field couples to the rest of the standard model*. It is at once complementary to the other two kinds of tests, and a uniquely powerful probe of fundamental physics in its own right.

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